

A Natural Explanation for Magnetars

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Neutron stars possess some of the strongest magnetic fields known in the universe. The surface magnetic fields of radio pulsars are estimated to be in the range 10^8 to 10^{13} Gauss, with 10^{12} Gauss being the typical value. Magnetars, a class of neutron stars with even stronger magnetic fields, $\sim 10^{15}$ Gauss, are believed to be “magnetically powered” stars, deriving most of their radiative luminosity at the cost of their magnetic fields. The origin of the strong magnetic fields of neutron stars, in particular those of magnetars, has essentially been an open question for decades. In this paper we explore the possibility that a magnetar may owe its strong field to a magnetized core which, as indicated by certain equations of state, may form due to phase transitions at high density mediated by strong interaction within a sufficiently massive neutron star. We argue that the field derived from such a core could explain several inferred evolutionary behaviors of magnetars.

Keywords: neutron star; magnetic field; strange matter; pion condensate

I. INTRODUCTION

Magnetars are neutron stars with surface magnetic fields a thousand times larger than that of an average pulsar. However, this is not their most distinctive property. While in pulsars, the loss of rotational energy can account for all of the observed radiation, in magnetars this is not so. The magnetars exhibit spin down ages $\sim 10^4$ years. Over this period, they emit a quiescent radiative luminosity $\sim 10^{35} - 10^{36}$ erg/s. In addition, some of them emit repeated flares or bursts of energy typically $\sim 10^{42} - 10^{44}$ erg, and at times much higher: $\sim 10^{46}$ erg (e.g. the very energetic flare of SGR1806-20 on 27 December 2004 [1, 2]). The energy emitted in both quiescent emission and flares far exceeds the loss in their rotational energy over the same period. The only known source of energy for these emissions is their magnetic energy [3, 4], yet their spin history appears to present no clear evidence of a decrease in their surface magnetic fields with time [5].

The range of spin periods in which magnetars have so far been found is surprisingly narrow, between 5 and 12 seconds. While the absence of shorter periods can be attributed to rather fast spin down due to their strong magnetic field, the upper cutoff in the spin period distribution implies a sudden ceasing of magnetar activity while their magnetic fields are still strong.

The distinct radiative property of magnetars indicates that they have an internal state different from that of ordinary radio pulsars. During their active period magnetars must have a transient store of free energy which dissipates as the observed radiation. In this paper we show that if in the collapse of the progenitor to a neutron star, the strong interaction creates a strongly magnetic core, most of the magnetar behavior can be explained. The magnetic field of the core will initially be screened by the conducting exterior. As this configuration relaxes, magnetic free energy is released and drives the magnetar activity. In section II below, we discuss the evolution of the magnetic field expected in the presence of a strongly magnetised core. In section III we discuss how, in certain equations of state of neutron star matter, such a strongly magnetized core could naturally arise. Section IV summarises our conclusions.

II. MAGNETIC FIELD EVOLUTION IN MAGNETARS

We start with the assumption that in the collapse of the protostar, a magnetized core is created in the newly formed neutron star with typical fields at the core surface of $\sim 10^{15} - 10^{16}$ gauss. Any dynamically generated field due to spin alignment via strong interaction is expected to be of this magnitude, which roughly equals the product of the nuclear magneton and the baryon number density in the neutron star interior.

It is unlikely that the magnetic moment of the core will manifest itself in a corresponding magnetic field on the neutron star surface immediately upon its formation. The material surrounding the core is a pre-existing, highly conducting, neutron-proton-electron (npe) plasma. As the core undergoes a phase transition to the magnetic phase, this surrounding npe plasma will see the magnetic field rise at the core boundary in a time scale set by causality, $\gtrsim r_{\text{core}}/c \sim 10^{-5}$ sec, which is much longer than its inverse plasma frequency, $\sim 10^{-21}$ s. Here r_{core} is the radius of the magnetic core. In reality the rise time of the field at the core boundary may be much longer: the phase transition may start in small islands, which will then have to come together and merge to form a coherent macroscopic structure. The islands may in principle have arbitrary magnetic orientation with respect to each other, but any pre-existing magnetic field, inherited by the star from its progenitor, will serve to define the orientation of the magnetic moments of these small regions, and hence also determine the orientation of the net magnetic moment of the core. It therefore appears that the core magnetic field will establish itself over a timescale long enough for the surrounding npe plasma to set up screening currents, as per Lenz’s law, to prevent the penetration of the magnetic flux through it. In this state, the magnetic field due to the core will be squeezed into a tight volume inside the star, around r_{core} , while an outside observer will have no knowledge of it. This magnetic configuration has a much higher energy than a relaxed, dipole distribution of the magnetic field outside the core. Typically, if the magnetic flux is confined within a radius r , its magnetic energy would be proportional to r^{-1} . For a core radius $\lesssim 50\%$ of the stellar radius, the excess magnetic energy would be of the same order as the energy in the relaxed dipole configuration.

With time, the magnetic field will tend to relax to the dipole configuration of lower energy, releasing the excess magnetic energy in the process. This will happen because the screening currents have a finite lifetime—they will be eventually killed by dissipative processes such as ohmic dissipation and ambipolar diffusion [6]. Time scales for these processes, relevant to npe plasma in the interior of a neutron star, have been worked out by Goldreich and Reisenegger [7]. Their estimates show that for typical temperatures in the neutron star interior, the ohmic dissipation time scale would be very long: $\geq 10^{11}$ y. Ambipolar diffusion will, however, play a very important role, with a dissipation time scale $\sim 5 \times 10^4 / (B_{16}^2 T_{8.5}^6)$ y, where B_{16} is the local magnetic field strength in unit of 10^{16} G and $T_{8.5}$ is the temperature in units of $10^{8.5}$ K, a typical value in the interior of a young neutron star. This would suggest that the strong magnetic field will emerge at the neutron star surface in the time scale of a few times 10^4 y. The excess magnetic energy will be dissipated over this period, driving an average radiative luminosity $\sim 10^{35} - 10^{36}$ erg/s. These estimates are in good agreement with the inferred ages and observed average luminosities of magnetars. For a radius of the core about half the stellar radius or less, the total free energy stored in the initial magnetic configuration would be sufficient to explain the observed level of magnetar activity over a duration of $\geq 10^4$ yr. The ongoing dissipation will also serve to keep the stellar interior hot enough for ambipolar diffusion to proceed in a reasonably short time scale, despite its extreme temperature sensitivity. If the local temperature tends to rise significantly above $10^{8.5}$ K, cooling via neutrinos will be dominant and will maintain the temperature at this level. This may well happen in the early stages, when the energy is released deep into the stellar interior [8]. In this phase the X-ray emission from the surface may be relatively faint. The young (~ 1700 y), high magnetic field ($\sim 4 \times 10^{13}$ G) radio pulsar J1119-6127 with faint X-ray emission from an unusually hot surface may in fact be an example of a star passing through this phase [9].

As the excess magnetic energy is dissipated, the magnetic field at the stellar surface will rise, eventually reaching the full dipole value corresponding to the core magnetic moment. This is contrary to what has been normally assumed in the literature – that the magnetic field of a magnetar should decrease with time as a consequence of dissipation of magnetic energy. One way of estimating the magnetic fields of magnetars is from their spin-down rate, attributing the spindown torque to that due to vacuum magnetic dipole radiation or equivalent. The same technique is used to estimate the magnetic fields of radio pulsars [10]. The recorded spin-down history of magnetars, however, shows no evidence of a secular decrease in their surface magnetic field. If at all, there is a mild evidence in favor of the magnetic field strength increasing with time [5]. A similar trend of increasing field strength has been noted in certain glitching radio pulsars too [11].

Magnetars can be classified into two broad categories: Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs) (see Woods and Thompson [12] for a recent review). SGRs are objects that show relatively frequent burst and flare activity. They also possess, on an average, somewhat stronger magnetic fields. AXPs represent a quieter magnetar population. Burst activity in them is rare, and their average field strength is smaller than that of SGRs. In the conventional

scenario, AXPs would be the later evolutionary products of SGRs [12]. In our model, SGRs, with stronger fields, would be older than AXPs. As these neutron stars are born in supernova explosions, and happen to be just $\sim 10^4$ y old, they are expected to be found associated with the remnants of these supernovae. Association with Supernova Remnants (SNRs) has indeed been found in several of these cases. Interestingly, the AXPs are found to be located close to the centers of the remnants while SGRs are often located far from the centers of the associated SNRs [5]. Given that all neutron stars receive some kick at birth, these observed offsets with respect to the SNR centers could be interpreted as the SGRs being older, and hence having had a longer time to drift away [5]. SGRs have smaller spindown ages ($\equiv P/2\dot{P}$) than AXPs, but as noted by Thompson, Lyutikov and Kulkarni [5] this may simply reflect an accelerated growth of the surface magnetic field in this phase, which is expected to happen as the strong magnetic field breaks through the upper crust [3, 4].

In the time sequence leading to the emergence of the magnetic field at the surface of the star, the leading ambipolar diffusion zone moves out from the interior of the star to the outer surface. Younger objects, where the activity is deeper sub-surface, are expected to have a relatively quiet existence, the dissipated heat being conducted out to the surface and radiated away, powering a quiescent X-ray luminosity. As the object ages and the strong field moves through the outer crust, mechanical disturbances of the crust could be triggered by the magnetic pressure, leading to glitches and flares. This trend would qualitatively fit the difference in the level of burst activity observed in AXPs and SGRs. The yield strength of the upper crust would be unable to support stresses for magnetic field gradient across the crust of $\geq 10^{13}$ G, as the maximum stress that the crust can support is estimated to be $\leq 10^{27}$ dyne cm^{-2} [13]. It is therefore likely that in this phase of evolution the magnetic field will eventually attain its relaxed configuration via several hundreds of SGR-type bursts.

We have mentioned above that the upper cutoff of the spin period distribution of magnetars at ~ 12 s implies a sudden ceasing of magnetar activity while their magnetic fields are still strong. For this there has so far been no natural explanation (see [14] for a discussion). In our model, this abrupt stoppage of magnetar activity is in fact expected. Once all the screening currents dissipate away and the magnetic field reaches its fully relaxed configuration, there is no more free energy available in the magnetic field to power the magnetar activity. Upon reaching this state, the luminosity of the magnetar will plummet and it will disappear from view. As the time scale for the emergence of the field is inversely proportional to B^2 and the spindown torque on the star is proportional to B^2 , it would be natural to expect that at the end of the magnetar activity the spin periods of these stars will be roughly similar [15].

In the post-magnetar phase the spin periods of these neutron stars will continue to lengthen, and they may function as long period rotation-powered radio pulsars. Careful surveys sensitive to pulsars with tens of seconds period may be able to find them. It is to be noted, however, that the active lifetimes of pulsars is inversely proportional to their magnetic field and hence the population of such long period, high field pulsars is expected to be much smaller than the garden variety radio pulsars with teragauss surface field.

III. ORIGIN OF MAGNETIC CORES IN NEUTRON STARS

In the discussion above we have assumed the presence of a strongly magnetized core in the neutron stars that act as magnetars. There are several scenarios in which such core magnetic fields can be created dynamically via a phase transition at high density for strongly interacting matter. To name a couple of possibilities,

1. In classic old fashioned nuclear high density ground states, large macroscopic magnetic moment can be generated by the alignment of nuclear spins, often accompanied by pion condensation (e.g. [16, 17]).
2. It is considered more plausible that at typical neutron star central densities ($\sim 5 - 6$ times nuclear density) we expect the nucleons to dissolve into quark matter. We have found that the likely ground state of such matter at these densities is a neutral pion condensate [18, 19]. Such a state carries a large magnetic moment *and hence can give rise to a strongly magnetized core*.

Both these cases involve a phase transition to a condensate, with condensation energies of order several tens of MeV per baryon (see, e.g., ref. [20]), corresponding to transition temperatures in excess of 10^{11} K. The interior temperature of a neutron star would fall well below this within a day after formation [21, 22], resulting in the formation of a magnetic core.

Several other equations of state of quark matter have been considered in the literature. One that has attracted much interest of late is that with a diquark superconductivity [23, 24]. A transition to such a state is expected at high density (~ 10 times nuclear density). Ferrer and de la Incera [25] have considered a scenario where strong magnetic fields can be produced by the generation of gluon vortices in the colour superconducting cores of neutron stars. This mechanism achieves an amplification of a pre-existing strong ($\sim 10^{17}$ G) field. On the other hand, the magnetic pion condensate mentioned above can spontaneously generate magnetar strength fields (see fig. 1).

We now present some considerations that will demarcate regions in the parameter space that can support quark matter Pion Condensed cores and those which are purely nuclear.

The magnetic pion condensed ground state of quark matter from an effective intermediate chiral lagrangian was first considered by Kutschera et al [19] for two-flavor quark matter. We have generalised the effective lagrangian, L , to 3 flavours, which can be used over a large range of densities, from nuclear matter to quark matter. We have also, for the first time, fixed all the coupling parameters of, L , from low energy hadronic data (see [26] for details). One of the parameters is the (tree-level) mass of the Sigma particle which is related to $\pi\pi$ scattering, and is estimated to be around $m_\sigma \sim 800$ MeV [27].

We have carried out this calculation for charge neutral, three-flavor quark matter in β equilibrium. This includes strange quarks as well as one-gluon exchange interactions. We have shown in an earlier work [18] that if m_σ exceeds ~ 700 MeV, then according to this mean field theory, the quark matter, rather than being in the conventional strange quark matter (SQM) state [28], would find it energetically favorable to organize itself into a chiral π^0 Pion Condensate (PC) which is spin polarized. Our calculations [26] show that

in the PC state that is realized, at the densities of interest, in the presence of the π^0 condensate the strong interaction causes the u-quark quasiparticles to align their spins along the condensate wave vector \vec{q} and the spins of d-quark quasiparticles to align the opposite way. The two species being oppositely charged, their magnetic moments then add, giving rise to local magnetic fields of order 10^{16} G. We estimate the magnetic moment density as $e\hbar(2S_u + S_d)/3mc$, where S_u and S_d are the spin densities of u and d quarks respectively. The quark mass m is set to $g < \sigma >$, g being the Yukawa coupling constant between the meson and the quark fields, which is set to 5.4 (see ref. [29]) by fixing the nucleon mass to be 938 MeV.

The equation of state of this PC matter has been derived and presented in [26], where we also discuss the structure of neutron stars that would result when the PC quark matter resides in the core. The outer part of the star is made up of nuclear matter, for which we adopt the equation of state derived by Akmal et al [30] (APR), used commonly in the literature. The boundary between the nuclear and the quark matter PC phase is treated as a first order phase transition. The main results are as follows.

A. The quark matter PC core regime (750 MeV < m_σ < 850 MeV)

1. In this model, the parameter m_σ is constrained to be above 750 MeV, to ensure that the two-flavor ground state does not fall below the nuclear ground state [18].
2. The maximum mass of neutron stars with PC cores works out to be $M_{\text{max,PC}} \sim 1.6 M_\odot$, as in most other cases of neutron stars with quark matter core. In contrast, the maximum mass of a purely nuclear star with APR equation of state is $\sim 2.2 M_\odot$.

The equation of state for PC quark matter employed by us includes gluon interactions as given by Baym [17, 37]. Other prescriptions for this exist in the literature, and some attempts have led to the mass limit of a star with a quark core being raised to as high as $\sim 2 M_\odot$ [31, 32].
3. The PC quark matter core occurs only if the mass of the star exceeds a threshold value M_T . Below this threshold mass the star is composed entirely of nuclear matter. The threshold mass is a function of the parameter m_σ . With increasing m_σ , the density of phase transition between the APR and PC phases rises and so does M_T . For an m_σ of 815 MeV, M_T works out to be $1.32 M_\odot$. A value of $m_\sigma > 850$ MeV results in M_T rising above $M_{\text{max,PC}}$ and thereby precludes the formation of a PC core. Neutron stars with quark matter PC cores can therefore exist only if m_σ is in the range 750–850 MeV.

To find the contribution of the PC core to the stellar magnetic field we estimate the magnetic moment μ by integrating the magnetic moment density over the volume of the PC core. The effective polar field strength at the stellar surface in fully relaxed configuration may then be computed as: $B_s = 2\mu/R^3$, where R is the stellar radius. The result, for two different values of m_σ , are shown in fig. 1. As can be seen, B_s has a typical

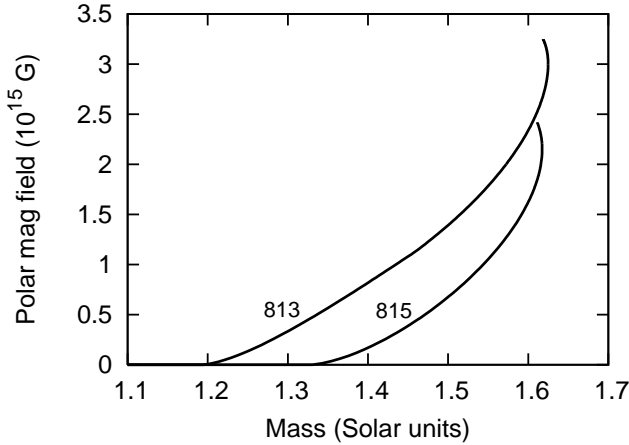


FIG. 1: The polar magnetic field strength at the surface of a neutron star containing pion-condensed quark matter core. The surface field strength is estimated for a fully relaxed dipole configuration corresponding to the magnetic moment of the core, shown for two values of the parameter m_σ , 813 and 815 MeV. The core appears above a threshold mass and if present, could generate surface fields of strength similar to those seen in magnetars.

value of $\sim 10^{15}$ G, similar to the fields encountered in magnetars. The field strength increases with the mass of the star above the threshold mass, and reaches $\sim (2-3) \times 10^{15}$ G near the maximum mass.

If magnetars do indeed owe their magnetic fields to such pion cores, their masses must exceed M_T . Ordinary pulsars, with much weaker magnetic fields ($\sim 10^{12}$ G), may then represent a neutron star population with masses less than M_T , their magnetic fields being either inherited from their progenitors [33], or amplified in the crust by thermoelectric processes [34]. This can be tested if the masses of magnetars can be measured, perhaps when magnetars in binary systems are found. Masses of several pulsars are known, and in most cases lie close to $\sim 1.4 M_\odot$.

B. The Purely Nuclear Matter star regime ($m_\sigma > 850$ MeV)

At high density (above $\sim 2-3$ times nuclear density) the nuclear matter itself can have a neutral pion condensate [16, 17], in which nuclear spins, aligned due to the presence of the neutral pion condensate, can contribute a strong magnetic field. For $m_\sigma > 850$ MeV the quark matter - nuclear matter transition density rises such that only fully nuclear stars are stable and can continue to exist. Since it is possible in a purely nuclear matter star at high enough density to have nuclear PC core, we then have a nuclear matter analogue for the lower threshold mass, M_T^N for nuclear magnetars with a new and higher maximum mass M_{max}^N of the star (as purely nuclear EOS's are stiffer).

We point to this possibility as one object, PSR J0751+1807 has recently been found to be relatively heavy, with a mass of $2.1_{-0.5}^{+0.4} M_\odot$ [35]. While this is still marginally consistent with $M_{max,PC}$, if future measurements confirm it to be larger than $\sim 1.6 M_\odot$ then the existence of pure quark matter PC core in neutron stars would be ruled out. Core magnetic fields

through spin alignment may still be produced, but perhaps in a pion-condensed nuclear phase [16] or a mixed phase [36] and the rest of the magnetar scenario would remain the same as above.

This discussion was to indicate that magnetars are possible both with a PC quark matter core or with a PC nuclear core. However if a neutron star with mass above $\sim 1.6 M_\odot$ is found then this would preclude pure quark matter core for all stars. However, as we have indicated above, it is possible that a different treatment of gluon interactions may raise the mass limit of stars with PC quark cores, as has been obtained in some equations of state involving quark matter [31, 32].

C. Magnetar by birth or accretion

Neutron stars with a large mass could result either, (i) from the core collapse of a rather massive star or (ii) by heavy accretion onto a neutron star in a binary system. In either case, if the final mass exceeds M_T , a magnetic pion core will form. Will one expect to see a magnetar in all such situations? The answer depends on the details of the thermal structure in the neutron star interior.

(i) A newly born neutron star in a stellar collapse has a very hot interior, facilitating ambipolar diffusion and allowing the strong field to emerge at the surface in a short time, as discussed above. The more massive the neutron star, the larger will be the size of the magnetic core and the quicker will the strong field emerge to the surface. It is interesting to note that possible magnetar activity has been indirectly inferred in the ~ 350 yr old supernova remnant Cassiopeia A [38], which originated in the explosion of a star as massive as $\sim 25 M_\odot$ [39]. Most importantly, recent observations [40] have uncovered several cases of association between magnetars and massive star clusters indicating that the progenitors of these neutron stars were more massive than $\sim 30 M_\odot$. A similar conclusion is drawn in the case of AXP 1E 1048.1-5937 which is associated with a stellar wind-blown shell of neutral hydrogen [40].

(ii) A neutron star accumulating matter via accretion, on the other hand, is old and its interior is relatively cold. Heating due to the accretion process is not expected to raise the interior temperature above $\sim 10^8$ K [41]. The extreme temperature sensitivity of the ambipolar diffusion rate will then delay the emergence of the field at the surface, perhaps for such a long time that the magnetar property would never be visible. This may be the reason why the surface magnetic field PSR J0751+1807 remains low [35] despite its mass growing to a large value.

IV. CONCLUSIONS

We have found that in certain allowed equations of state of neutron stars a strongly magnetized pion condensed core occurs at high density, for neutron star masses near the maximum mass. We have argued that such stars would have properties remarkably similar to the observed magnetars. The magnetic field of the core would initially be squeezed deep into the star due to screening currents set up in the material

surrounding the core. The free energy in this field configuration would be released over a time scale of $\sim 10^4$ yr and power the magnetar activity. Along with this, the magnetic field at the surface will rise, possibly turning Anomalous X-ray Pulsars into Soft Gamma Repeaters. If this model for magnetars is correct, then magnetars would be expected to have masses higher than a certain threshold, and would therefore be expected to be associated with supernova explosions from relatively massive stars. Neutron stars with magnetic cores may also be produced by heavy accretion onto normal neutron stars in binary systems, although it seems less likely that the magnetic field will emerge to the surface quickly enough to exhibit magnetar activity in this case. If a magnetar in a binary system is found, several of these predictions could be tested.

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- [1] D.M. Palmer et al., *Nature* **434**, 1107 (2005)
 - [2] K. Hurley et al., *Nature* **434**, 1098 (2005)
 - [3] R.C. Duncan & C. Thompson, *Astrophys. J.* **392**, L9 (1992)
 - [4] C. Thompson & R.C. Duncan, *Mon. Not. R. Astron. Soc.* **275**, 255 (1995)
 - [5] C. Thompson, M. Lyutikov & S.R. Kulkarni, *Astrophys. J.* **574**, 332 (2002)
 - [6] L. Spitzer, *Physical Processes in the Interstellar Medium*, John Wiley & Sons, New York (1978)
 - [7] P. Goldreich & A. Reisenegger, *Astrophys. J.* **395**, 250 (1992)
 - [8] A.D. Kaminker, D.G. Yakovlev, A.Y. Potekhin, N. Shibazaki, P.S. Shternin & O.Y. Gnedin, *Mon. Not. Roy. Astron. Soc.* **371**, 477 (2006)
 - [9] M.E. Gonzalez, V.M. Kaspi, B.M. Gaensler & M.J. Pivovarov, *Astrophys. J.* **630**, 489 (2005)
 - [10] R.N. Manchester & J.H. Taylor, *Pulsars*, W.H. Freeman, San Francisco (1977)
 - [11] S.N. Zhang & J. Lin, talk presented at the Urunci meeting on Radio Pulsars (2005)
 - [12] P.M. Woods & C. Thompson, in "Compact Stellar X-ray Sources", eds. W.H.G. Lewin and M. van der Klis, Cambridge University Press, p. 547 (2006)
 - [13] M. Ruderman, *Astrophys. J.* **366**, 291 (1991)
 - [14] M. Colpi, U. Geppert & D. Page, *Astrophys. J.* **529**, L29 (2000)
 - [15] A. Reisenegger, private communication (2007)
 - [16] F. Dautry & E.M. Nyman, *Nucl. Phys.* **A319**, 323 (1979)
 - [17] G. Baym, *Neutron Stars and the Properties of Matter at High Density*, NORDITA lectures (1977)
 - [18] V. Soni, & D. Bhattacharya, *Phys. Rev.* **D69**, 074001-1 (2004)
 - [19] M. Kutschera, W. Broniowski & A. Kotlorz, *Nucl. Phys.* **A516**, 566 (1990)
 - [20] M. Sadzikowski & W. Broniowski, *Phys. Lett. B* **488**, 63 (2000)
 - [21] C.J. Pethick, *Rev. Mod. Phys.* **64**, 1133 (1992)
 - [22] D.G. Yakovlev & C.J. Pethick, *Ann. Rev. Astron. Astrophys.* **42**, 169 (2004)
 - [23] M. Alford, K. Rajagopal & F. Wilczek, *Phys. Lett. B* **422**, 247 (1998)
 - [24] R. Rapp, T. Schafer, E.V. Shuryak & M. Velkovsky, *Phys. Rev. Lett.* **81**, 53 (1998)
 - [25] E.J. Ferrer & V. de la Incera, *Phys. Rev. Lett.* **97**, 122301 (2006); *astro-ph/0611460* (2006)
 - [26] V. Soni, & D. Bhattacharya, *Phys. Lett. B*, **643**, 158 (2006). See also V. Soni & D. Bhattacharya, *hep-ph/0504041* (2005)
 - [27] A. Abdel-Rehim, D. Black, A.H. Fariborz, S. Nasri & J. Schechter, *Phys. Rev.* **D68**, 013008-1 (2003)
 - [28] E. Witten, *Phys. Rev.* **D30**, 272 (1984)
 - [29] M.C. Birse & M.K. Banerjee, *Phys. Lett.* **B136**, 284 (1984)
 - [30] A. Akmal, V.R. Pandharipande & D.G. Ravenhall, *Phys. Rev.* **C58**, 1804 (1998)
 - [31] M. Alford, D. Blaschke, A. Drago, T. Klähn, G. Pagliara & J. Schaffner-Bielich, *astro-ph/0606524* (2006)
 - [32] M. Alford, M. Braby, M. Paris & S. Reddy, *Astrophys. J.* **629**, 969 (2005)
 - [33] L. Woltjer, *Astrophys. J.* **140**, 1309 (1964)
 - [34] R.D. Blandford, J.H. Applegate & L. Hernquist, *Mon. Not. Roy. Astron. Soc.* **204**, 1025 (1983)
 - [35] D.J. Nice, E.M. Splaver, I.H. Stairs, O. Löhmer, A. Jessner, M. Kramer & J.M. Cordes, *Astrophys. J.* **634**, 1242 (2005)
 - [36] N.K. Glendenning, *Phys. Rev.* **D46**, 1274 (1992)
 - [37] G. Baym & S. Chin, *Phys. Lett. B* **62**, 241 (1976)
 - [38] O. Krause *et al.*, *Science* **308**, 1604 (2005)
 - [39] J. Vink, *New Astron. Rev.* **48**, 61 (2004)
 - [40] M.P. Muno, *astro-ph/0611589* (2006)
 - [41] J.L. Zdunik, P. Haensel, B. Paczyński & J. Miralda-Escudé, *Astrophys. J.* **384**, 129 (1992)